Research

Cite this article: Hayek JN, Vilacís B, Bunge H-P, Friedrich AM, Carena S, Vibe Y. 2020 Continent-scale Hiatus Maps for the Atlantic Realm and Australia since the Upper Jurassic and links to mantle flow induced dynamic topography. *Proc. R. Soc. A* **476**: 20200390. <http://dx.doi.org/10.1098/rspa.2020.0390>

Received: 17 May 2020

Accepted: 4 September 2020

Subject Areas:

geophysics, geology

Keywords:

dynamic topography, geological maps, chronostratigraphy, Hiatus, mantle convection, global geodynamics

Author for correspondence:

Jorge Nicolas Hayek

e-mail: jhayek@geophysik.uni-muenchen.de

Electronic supplementary material is available online at <https://doi.org/10.6084/m9.figshare.c.5132761>.

Continent-scale Hiatus Maps for the Atlantic Realm and Australia since the Upper Jurassic and links to mantle flow induced dynamic topography

Jorge Nicolas Hayek, Berta Vilacís, Hans-Peter Bunge, Anke M. Friedrich, Sara Carena and Yulia Vibe

Ludwig-Maximilians-Universität München, Department of Earth and Environmental Sciences, Theresienstraße 41 and Luisenstraße 37, 80333 Munich, Germany

JNH, 0000-0002-0351-3368; BV, 0000-0001-5597-2606

Interregional geological maps hold important information for geodynamic models. Here, we use such maps to visualize major conformable and unconformable contacts at interregional scales and at the level of geologic series from the Upper Jurassic onward across North and South America, Europe, Africa and Australia. We extract hiatus information from these paleogeological maps, which we plot in a paleogeographical reference frame to link the maps to the plate and plume modes of mantle convection. We assume that interregional patterns of hiatus surfaces are proxy records of continent-scale mantle-induced vertical motion of the lithosphere. We find significant differences in the distribution of hiatus across and between continents at the timescale of geologic series, that is ten to a few tens of millions of years (Myrs). This is smaller than the mantle transit time, which, as the timescale of convection, is about 100–200 Myrs. Our results imply that different timescales for convection and topography in convective support must be an integral component of time-dependent geodynamic Earth models, consistent with the presence of a weaker upper mantle relative to the lower mantle. Additional geological constraints together with interregional geological maps at the resolution of stages (1–2 Myrs), are needed to assist in future geodynamic interpretations of interregional geologic hiatus.

1. Introduction

An early success in geodynamics was the quantitative description of mantle convection by a boundary-layer model of high Rayleigh number and low Reynolds number flow [1]. The model came into its own when mantle convection was explored explicitly in terms of the plate and plume mode [e.g. [2–4]]. The former is associated with the cold upper thermal boundary layer, which is the lithosphere, and the latter with the hot lower thermal boundary layer, which sources plumes.

The plate mode has since then been mapped by kinematic models of lithosphere motion for the Cenozoic [5] and Mesozoic (e.g. [6]). Its temporal evolution has been linked to the generation of large-scale mantle heterogeneity through the history of subduction [7,8] and assimilated into global mantle convection simulations [9–11] to construct mantle circulation models, which from here on we will call MCM. Recently, the plume mode has been imaged by seismic tomography as localized upwellings that rise from the core-mantle boundary (CMB) to the base of the lithosphere [12–14], and the boundary-layer nature of mantle convection is now widely recognized.

Geodynamicists also understood early on that mantle convection deflects the Earth's surface away from its isostatically compensated state [15]. Termed 'dynamic topography' by Hager *et al.* [16] the deflections are receiving renewed attention (e.g. [17]), particularly as an agent in passive margin environments [18], where the proximity to a base level allows one to gauge topographic changes better than at other places.

The boundary-layer interpretation of mantle flow makes it convenient to interpret the sedimentary expression of dynamic topography explicitly in terms of the plate and plume modes. For the plate mode, the approach was pioneered using the sedimentary record from the *Cretaceous Interior Seaway* and the cratonic interior of North America (e.g. [19,20]) because surface depressions induced by mantle downwellings in these regions left accommodation space to preserve a sedimentary archive. Other regions, such as the Cretaceous Eromanga Sea in Australia [21,22] and a regional unconformity of Cretaceous-Eocene age in southeast Asia [23] also record plate-mode-related vertical motion. Recently, MCMs have modelled the evolution of plate-mode-related dynamic topography since the Cretaceous [24].

It is more difficult to map the stratigraphic expression of the plume mode because the positive surface deflections create erosional / non-depositional environments, which leave time gaps in the sedimentary record. Field observations of the surface expression of the plume mode document changes in drainage patterns (e.g. [25]) and a dome-shaped uplift of 1–2 km (e.g. [26–28]) over a radius of 1000–2000 km. The resulting discontinuity surfaces in the sedimentary record are known as unconformities (e.g. [29]), although their wavelengths are so large and their amplitudes so little that at large distances an unconformity may locally be recorded as a disconformity. They preserve time missing (hiatus) from the geological record [30]. To this end, an approach of hiatus-area mapping was introduced [30,31] to highlight the long-wavelength nature of sedimentation records as explored by Sloss [32,33]. It visualizes interregional-scale unconformities because, at continental scales, what is normally perceived as a lack of data (material eroded or not deposited) becomes part of the dynamic topography signal. The method has been applied to map the temporal and spatial patterns of conformable and unconformable geological contacts across Europe [34] and Africa [35].

Continent-scale geological maps, such as the 1:5 Million International Geological Map of Europe and Adjacent Areas (IGME 5000) [36], are crucial databases to reveal hiatus area of geodynamic origin, that is falcogeny in the sense of Şengör [37]. They provide internally consistent compilations of geological observations, including chronostratigraphic age, lithology and geolocalization of the strata, at the scale of thousands of kilometres. This links them naturally to continent-scale elevation changes induced by mantle flow. Here, we explore interregional-scale geological maps. We identify temporal and spatial patterns of geological hiatus contacts across North and South America, Europe, Africa and Australia, under the assumption that interregional-scale conformable and unconformable contacts are proxy records of paleotopography and vertical motion. We organize our paper as follows: first, we explain our hiatus mapping method. Then we present results starting from hiatus maps for the Upper Jurassic. We find significant differences in

the spatial extent of hiatus area across and between continents at the timescale of geologic series, ten to a few tens of millions of years (Myrs), which is considerably smaller than the mantle transit time [38]. We note that this negates the concepts of Stille [39,40] and Sloss [33], who argued for global synchronicity cycles. Finally, we discuss our results, place them into a geodynamic context, explore their implications for dynamic Earth models, and draw conclusions.

2. Data compilation, preparation and uncertainties

We mapped conformable and unconformable contacts at the resolution of geological series because this is the most frequently adopted temporal resolution among interregional geologic maps [31]. We also opted to map hiatus from the Upper Jurassic onward, to remain within a timescale comparable with the mantle transit time, which is about 100–200 Myrs [38]. To this end, we took the digital vector maps of Europe, Australia and North America, which describe the chronostratigraphic units within specific temporal and spatial resolutions. For South America, we compiled individual country-scale information, since only this was available at the temporal resolution of series.

Diverse open-access databases [36,41–51] provide digital information from geological maps as vector files. Some maps include information from the continental shelf and other seafloor features. We did not use this information because it also includes magnetic isochron data, which are not related to the sedimentation paleoenvironment. However, oceanic pointwise information in the form of localized stratigraphic columns from the Ocean Drilling Program (ODP) can record oceanic hiatus events. For this reason, we imported offshore data from ODP [52] Legs 100–190 and Deep Sea Drilling Project (DSDP) [53] Legs 1–95. Additionally, we used [35] for the Cenozoic series of Africa augmented by further information for the Upper and Lower Cretaceous. Table 1 summarizes our compilation of geological information. The geological maps published at continent and country scale vary both in spatial and temporal resolution. Some maps are resolved at the series level. Others provide finer or coarser geological time intervals, such as combinations of series, stages or systems, as defined in the chronostratigraphic chart [54,55]. For instance, the map may state *Paleogene* for the units shown. Thus time resolution falls within three categories: series, series/stages/systems mix and systems. The maps moreover use distinct naming conventions for age descriptions, including different abbreviations, languages and aggregations of time units. To handle the diversity, we adopted a standardization procedure and harmonized the time resolution among the maps. We saturated all subseries information to the series level and brought the geological unit conventions to a standard reference. This translates languages, abbreviations and combinations or ranges of geological units to the numerical value of geological time. For instance, a polygon defined as *Oligocene-Miocene* or *Chattian-Langhian* time has the same time range after the standardization and spans two series (approx. 30 Myrs). For polygons with systems resolution we assigned the hiatus information to the base of the polygon's age range. For South America our procedure brought the country-specific maps to a unified continent-scale format. An exception had to be made for Argentina, where the temporal resolution was available only at the systems level.

Following Carena *et al.* [35], we define *conformity* if a target series sits atop the one immediately preceding it in the chronostratigraphic chart, regardless of whether either series has missing stages. We define *unconformity* as the complementary state to *conformity*. This holds for any place where one or more series immediately preceding the target series are missing. The definitions apply regardless of the physical contact type between both rock units. Figures 1 and 2 provide a schematic illustration of hiatus and the extraction process for un/conformable contacts [31]. To delimit hiatus for a given series, we also include in the maps any occurrence of the immediately preceding series and categorize the signal as conformable.

Since the temporal resolution is restricted to the series level, the un/conformity represents a time span that varies for different series. For instance, unconformity at the base of the Miocene datum is at least 11 Myrs, because this is the duration of the Oligocene series. Unconformity at the base of the Paleocene datum lasts a minimum of 34 Myrs, which is the duration of the Upper

Figure 1. (a) Schematic map (top) and perspective view (bottom) of geological units in conformable contact (blue lines). (b) Same scheme showing an unconformable contact (red line), where the middle unit is missing, representing a gap (hiatus) in the geologic record. (Online version in colour.)

Table 1. Geological maps used in this work with their respective spatial and temporal resolution. Compilations performed at the country level for South America (see text).

region		temporal resolution	spatial resolution	reference
Australia		series and stages	1 : 1 million	Geoscience Australia [41]
Europe		series	1 : 5 million	BGR [36]
North America		series and stages	1 : 5 million	USGS [42]
South America	Argentina	systems	1 : 2.5 million	SEGEMAR [43]
	Bolivia	series	1 : 1 million	SERGEOTECMIN [44]
	Brazil	series	1 : 250 000	CPRM [45]
	Chile	stages	1 : 1 million	SERNAGEOMIN [46]
	Colombia	stages	1 : 1 million	SGC [47]
	Ecuador	series	1 : 100 000	MAGAP [48]
	Peru	stages	1 : 100 000	INGEMMET [49]
	Uruguay	series	1 : 500 000	MIEM [50]
South America	Venezuela	series	1 : 500 000	USGS [51]
	Africa	series and systems	1 : 5 million*	[35]
Ocean Drilling Projects		series	—	[52,53]

* Africa hiatus information taken from [35] with hiatus information added for Upper and Lower Cretaceous. Offshore data imported from ODP [52] Legs 100–190 and DSDP [53] Legs 1–95 as pointwise signal.

Cretaceous series. We note, however, that the hiatus duration could be longer for either case. In the former, rocks of Lower and Middle Miocene and/or Upper and Middle Eocene could be missing. In the latter, rocks of Lower and Middle Paleocene and/or Lower Cretaceous could be absent. The uncertainty of a hiatus transforms into a spatial uncertainty when plate motions are taken into account. If we take the current global root mean square plate velocity of 5 cm yr^{-1} [56] as a representative value, temporal uncertainty for a hiatus at the series level (10–30 Myrs) translates into a minimum spatial uncertainty of 500–1500 km. Moreover, by saturating temporal resolution to the series level, we underestimate the total amount of hiatus because unconformities and hiatus at the resolution of stages may be masked at the stratigraphic resolution of series. Figure 3 illustrates these uncertainties.

Figure 2. (a) Schematic geological map for five consecutive chronostratigraphic units (T1 to T5) with T1 youngest and T5 oldest. (b) Schematic showing the extraction of un/conformable contacts for a target unit. Conformable lines for the target unit are the contours of the preceding unit. Unconformable contacts contour the contact of the unit with units older than the immediately preceding one. (Online version in colour.)

Figure 3. Schematic illustration of the temporal and spatial uncertainty of hiatus mapping [30,31,34,35]. Panels (a) and (b) show conformable and unconformable contacts, respectively. Panel (c) displays how temporal uncertainty translates into spatial uncertainty for the paleogeographical reconstruction representing hiatus. (Online version in colour.)

3. Results

(a) Geological Hiatus Maps

Figure 4 shows hiatus mapped with our method for North and South America, Europe, Africa and Australia for eight geologic series. This yields a set of eight Geological Hiatus Maps (GHMs), beginning with the Lower Cretaceous (i.e. hiatus here meaning that the Upper Jurassic is missing). We use *pyGPlates* [58] to reconstruct each hiatus to its past tectonic setting with a global Mesozoic-Cenozoic plate motion model [6] tied to a reference frame of Indo-Atlantic hotspots [57,59] and present the extracted signal in a plate tectonic configuration corresponding to the base of each series. Red and blue colours depict un/conformable contacts, respectively. Blank regions indicate the absence of the considered series and its immediately preceding unit.

In the following, we describe the results for each GHM. Base of Pleistocene datum, figure 4a, presents North and South America, Greenland and Australia with predominantly unconformable contacts. Conformable contacts exist in the High Plains of North America, parts of South America, and the Australian *Nullarbor Plain*. Europe is dominated by conformable contacts. Africa shows a mix of un/conformable contacts, with conformable contacts located in the northwest and in the Kalahari and Congo Basins. Unconformable contacts extend through the East African Highlands and the Sahara desert. Base of Pliocene datum, figure 4b, exposes conformable contacts in North and South America, around the Gulf of Mexico, the *Basin and Range*, the

Figure 4. Geological Hiatus Maps (GHMs) at chronostratigraphic division of series [54] from the Base of Pleistocene datum to the Base of Lower Cretaceous datum (*a–h*) reconstructed paleogeographically with a global Mesozoic–Cenozoic plate motion model [6] tied to a reference frame of Indo-Atlantic hotspots [57] and shown in a plate tectonic configuration corresponding to the base of each series. Red/blue points represent un/conformable contacts, respectively. Blank regions indicate the absence of considered series and its immediately preceding unit. See text for further information. (Online version in colour.)

Rocky Mountains front, the Brazilian Highlands and the western Amazon Basin. Australia shows sparse conformable contacts throughout the continent and isolated unconformable contacts in the north and in the southeast. Conformable contacts cover eastern Europe and the Iberian Peninsula, while unconformable contacts prevail in western/central Europe and in tectonically active regions in the Mediterranean. Africa exhibits unconformable contacts in the Congo Basin and the Canary-Atlas region, while conformable contacts occur in the Kalahari Basin, the Afar region and the northern edges of the continent. Base of Miocene datum, figure 4c, is dominated by unconformable contacts across the continents. Unconformable contacts abound in the western part of North America, Brazil and much of Europe, whereas isolated hiatuses exist in Australia and Africa. Conformable contacts are exposed in Greenland, western and easternmost Europe

and the Kalahari Basin. Base of Oligocene datum, [figure 4d](#), exposes conformable contacts in many regions, with a striking absence of signal across South America. Unconformable contacts are mapped in the western parts of North America, the Afar region and in Europe. Base of Eocene datum, [figure 4e](#), features a mix of signals. Unconformable contacts exist in eastern Africa, Europe and the western parts of North America adjacent to conformable contacts in the plains of Canada. South America lacks information except for conformable contacts in the eastern Amazon. Africa reveals conformable contacts in its northern parts and the Kalahari Basin, but signal is absent in the central and southern parts of the continent. Scattered unconformable contacts are mapped across Australia. Base of Paleocene datum, [figure 4f](#), reveals abundant conformable contacts across North and South America, Europe, Africa and Australia. Unconformable contacts are located in the northwestern part of North America and Greenland. South America exposes unconformable contacts along the Andes and the east coast of Brazil. Africa shows clusters of unconformable contacts in the Kalahari Basin, the northern Djoué Basin and the Afar region. Unconformable contacts are mapped in southern Australia near Tasmania. Base of Upper Cretaceous datum, [figure 4g](#), is characterized by unconformable contacts, which prevail across Africa, Europe and the western parts of North America. Conformable contacts are mapped in Canada, Mexico, the northern and eastern parts of Africa, the Parana region of South America and Australia. Finally, Base of Lower Cretaceous datum, [figure 4h](#), exhibits a mix of un/conformable contacts. Most notable are unconformable contacts in Alaska as well as a lack of signal throughout much of southern/central Africa and South America. We point out that the absence of Mesozoic/Cenozoic strata across much of Scandinavia and the cratonic part of North America precludes hiatus mapping for the Mesozoic/Cenozoic series in these regions.

(b) Base Hiatus Surfaces

The GHMs allow us to perform a spherical harmonics expansion of the hiatus signal to create Base Hiatus Surface (BHS). We adopted *pyshtools* [60] with fully normalized spherical harmonic coefficients [61], using a global equidistant grid of 720/1440 points in latitude/longitude for a resolution of ≈ 30 km between grid nodes. Numerical values of 1/−1 were assigned to un/conformable signal, respectively. Each grid node was then initialized with the nearest hiatus value that falls within a radius of 1/2 of the grid node distance. Otherwise, the grid node value was set to zero.

We performed the expansion up to spherical harmonic degree 100. However, our assumption of a geodynamic origin for interregional-scale hiatus implies the choice of a spectral window that one should consider in the BHS representations. Longstanding arguments based on dynamic models of the Geoid suggest a dominant contribution to dynamic topography of spherical harmonic degree 2 [62]. The dominance of the longest wavelength components for convectively maintained topography was challenged recently by an observational database of greater than 2000 spot measurements of residual bathymetry in the oceanic realm [63]. The latter suggests that contributions up to and including degree 30 are required to represent topography in convective support. [Figure 5](#) illustrates the difference and reports BHS for the Base of Miocene datum for four cut off degrees (2, 10, 15 and 30) and a tapered Gaussian smoothing to the spectral coefficients. The taper width of 40 degrees allows the contribution of spectral components beyond the cut off. For the long-wavelength cut off at degree 2 there remains a 30% contribution of the original signal at degree 27, while the degree 30 cut off maintains 30% of the original signal up to degree 55. We report BHS starting with the Lower Cretaceous and assuming an intermediate cut off at degree 15 in [figure 6](#).

The BHS provides information on the temporal evolution in the ratio of the area of conformal surface relative to the total area of conformal and unconformal surface. The latter can be plotted both aggregated over all continents and separate for each. The aggregated curve ([figure 7](#)) achieves a maximum in the ratio of conformable surface relative to the total area of conformable and unconformable surface at the Base of Paleocene (corresponding to topography of the Upper Cretaceous). There are also two prominent maxima in the ratio of the area of unconformable

Figure 5. Base of Miocene Hiatus Surface (BHS) obtained by expanding the Miocene Geological Hiatus Map (GHM) (figure 4c) in fully normalized [61] spherical harmonics (SH) and convolving with a Gaussian taper at four different cut off values for degree 2 (a), 10 (b), 15 (c) and 30 (d), respectively. Red/blue areas represent un/conformable surfaces. Black dotted lines contour the SH signal at the ± 0.1 amplitude. Hiatus data from the input GHMs are shown as blue/red dots. Centre plot: four Gaussian tapers applied in the SH expansion, see text. (Online version in colour.)

surface relative to the total area of conformable and unconformable surface at the Base of Miocene and the Base of Pleistocene, respectively. The curves for individual continents (figure 8) are more variable. They reveal considerable differences between continents and series.

4. Discussion

Geodynamicists have long recognized the essential role of dynamic topography in studies of the Geoid because the mass anomalies associated with surface deflections yield gravity anomalies of comparable amplitude with the flow-inducing mantle density variations. Geoid models therefore account for dynamic topography as well as mantle density heterogeneity (e.g. [62,69,70]). However, it is difficult to separate dynamic topography from topography in isostatic support [71–73] outside the oceanic realm [63]. This has led some to doubt the existence of dynamic topography [74].

The transient nature of dynamic topography suggests to overcome this difficulty by turning to geologic archives. Ahead of his time, Bond [75,76] analysed continent-scale sediment distributions to argue for substantial uplift of continental platforms. He concluded that Africa, for instance, experienced late Tertiary uplift relative to other continents [77], in agreement with Burke and Whiteman [78]. Our interregional hiatus maps also turn to sedimentary archives, in the form of interregional unconformities. But we note that the existence of such unconformities has long been known (e.g. [32,37,40,79–86]) and that some have pointed out the need of physical models for their interpretation (e.g. [20,86]).

Our GHMs locate sedimentary rocks of any origin, including volcanic effusive and pyroclastic products that, for the purpose of mapping depositional sequences, behave like sediments. Thus, to first order, the time slices in figure 4 show, where sediments were or were not deposited (or deposited and then eroded before the deposition of the next series) in the series immediately preceding the target series. Surfaces of unconformable contact (marked in red) in the BHS (figure 6) define regions in the series immediately preceding the target series that undergo erosion and/or non-deposition, whereas areas of conformable contact (marked in blue) identify

Figure 6. Base Hiatus Surface (BHS) obtained by expanding the Geological Hiatus Maps (GHMs) (figure 4) in fully normalized [61] spherical harmonics (SH) and convolving with a Gaussian taper starting at degree 15 (compare with figure 5). BHS shown at chronostratigraphic division of series [54] from the Base of Pleistocene to the Base of Lower Cretaceous (*a–h*) reconstructed paleogeographically with a global Mesozoic–Cenozoic plate motion model [6] tied to a reference frame of Indo–Atlantic hotspots [57] and placed into a plate tectonic configuration corresponding to the base of each series. Blue/red colours represent no-/hiatus surfaces, indicative of low/high topography in the preceding series, respectively. Black dotted lines contour the SH signal at the ± 0.1 amplitude. Hiatus data from the input GHMs are shown as blue/red dots. Black circles at Base of Miocene (*c*), Base of Eocene (*e*) and Base of Upper Cretaceous (*g*) maps correspond to the location of flood basalts associated with Afar, Iceland and Tristan hotspots [64]. Blank regions indicate the absence of series and its immediately preceding unit, suggesting long hiatus duration. See text for further information. (Online version in colour.)

depositional regions. At the interregional scales invoked, this serves as a proxy for either exhumation and surface uplift, or burial and subsidence. Lack of signal in the BHS indicates the absence of sediments in the target series and its immediately preceding series. This describes regions that may have undergone intense and/or long-lasting erosion or non-deposition and

Figure 7. Ratio of the area of un/conformal (solid red/blue lines) surface relative to the total area of conformal and unconformal surface aggregated over North/South America, Europe, Africa and Australia from the Base of Lower Cretaceous to the Base of Pleistocene, indicative of mean relative elevation (blue = low, red = high) across the continents in the preceding series (see text). The spherical harmonics (SH) area of conformal and unconformable surface is taken within the amplitude range (greater than or equal to 0.1) for a tapered cut off at degree 15 (figure 6). The // and \ \ shaded envelopes represent the ratio variations that correspond to tapered cut offs in the SH surface at degree 2 and 30, respectively (compare with figure 5). A maximum in the ratio of conformable surface at the Base of Paleocene (corresponding to mean topography in the Upper Cretaceous) relative to the total area of conformal and unconformal surface agrees with global sea-level curves (e.g. [65,66]). Two maxima in the ratio of unconformable surface relative to the total area of conformal and unconformal surface at the Base of Miocene and the Base of Pleistocene coincide with the onset of glaciation in Antarctica [67] and the Northern Hemisphere [68], respectively (see text). The total area (within the amplitude range (greater than or equal to 0.1) for a tapered cut off at degree 15) of conformal and unconformal surface relative to the total area of the considered continents is shown by the grey curve. The grey hatched // and \ \ shaded envelopes represent the ratio variations that correspond to tapered cut offs in the SH area at degree 2 and 30, respectively. (Online version in colour.)

suggests intense and/or persistent exhumation and surface uplift [30,31,34,35]. Examples for un/conformable surfaces and for lack of signal can be identified in the BHS.

South America reveals a continent-scale lack of signal at the Base of Eocene and the Base of Oligocene (figure 6*d,e*), indicating early Tertiary uplift in the region. This coincides temporally with the onset of rapid South Atlantic spreading rates [87] and an Eocene subaerial exposure of the Rio Grande Rise at Drill Site 516 [88]. There are also reports from thermochronological data and landscape analysis for post-rift Eocene reactivation in Brazil [89–91] and Argentina [92], and there is a Paleogene hiatus documented in Andean Foreland Basins [93].

Expansion of the total unconformable area from one time slice to the next indicates the onset of relative subsidence; it means that sediments now deposit in areas that previously underwent erosion/non-deposition. A significant expansion of unconformable area in central and northern Africa occurs at the Base of the Upper Cretaceous when compared with the Lower Cretaceous (figure 6*g,h*) and suggests that the Upper Cretaceous was a period of subsidence in Africa. An exception is the South African Plateau (SAP). It reveals a lack of signal suggestive of net high elevation. While this agrees with reports by some authors [94–96] calling for a Cretaceous age of the SAP topography, others suggest more recent Oligo-Miocene or younger uplift phases [35,97]. Another major expansion of unconformable area across Africa occurs at the Base of Miocene when compared with the Base of Oligocene (figure 6*c,d*). It implies relative subsidence in the Miocene and suggests that the Oligocene was a period of uplift in most of the continent, as noted by several authors [26,35,77] and reviewed very effectively by Burke and Gunnell [97]. A recent geologic/geodynamic analysis suggests that Africa may cover different dynamic topography domains owing to its large area. Carena *et al.* [35] took the presence of Upper Cretaceous to Eocene exposed marine sediments in the interior of northern Africa together with the absence of exposed

Figure 8. Same as figure 7, but for individual continents. The curves are more variable and reveal considerable differences between continents and series. See text for interpretation. (Online version in colour.)

Oligocene to Pleistocene marine sediments there as evidence that this region uplifted significantly after the end of the Eocene, remaining high since. Oligocene to recent sediments in northern Africa are exclusively of continental origin. Far less marine sedimentation exists in the southern half of Africa for the Cenozoic series, where it is limited to coastal regions. While none of the exposed Cenozoic sediments in the interior of southern Africa are marine, there is a complete absence of coastal marine sediments in the Oligocene and Pleistocene. From this, and from the observation that some Miocene and Pliocene marine sediments along the southern coast are now at elevations significantly above 200 m, Carena *et al.* [35] inferred that southernmost Africa reached a high elevation in the Oligocene, subsided in the Miocene–Pliocene, and has been high again since the Pleistocene.

Europe features a strong expansion of unconformable area at the Base of Eocene when compared with the Base of Paleocene (figure 6e,f), indicative of relative subsidence in the Eocene. We note that the above examples of expanding unconformable area follow each in the wake of major plume events (i.e. Tristan, Lower Cretaceous; Afar, Oligocene; and Iceland, Paleocene, see figure 6).

Conformable area expansion from one time slice to the next indicates continued subsidence [31,34,35]. Prominent examples include Australia at the Base of Upper Cretaceous when compared with the Base of Lower Cretaceous (figure 6g/h), and western North America at the Base of Paleocene when compared with the Base of Upper Cretaceous (figure 6f/g). Continent-scale subsidence implied by growing conformable area in these regions has been linked to subduction at the eastern margin of Gondwana [98,99] and to the descent of the Farallon Plate beneath western North America [19,20,100].

Figures 7 and 8 show the temporal evolution in the ratio of the area of un/conformal surface relative to the total area of conformal and unconformal surface, both aggregated over all continents and separate for each. The aggregated curve (figure 7) reveals a sea-level signal. It is indicated by a maximum in the ratio of the area of conformable surface at the Base of Paleocene (corresponding to the Upper Cretaceous) relative to the total area of conformal and unconformal surface. The maximum agrees with global sea-level curves even when the amplitude of the latter is not well constrained (e.g. [65,66]). There are also two prominent maxima in the ratio of the area of unconformable surface relative to the total area of conformal and unconformal surface at the Base of Miocene and the Base of Pleistocene. These coincide with the onset of glaciation in Antarctica [67] and the Northern Hemisphere [68], respectively.

The curves for individual continents (figure 8) provide additional information: a sharp decline for North America in the ratio of conformable surface relative to the total area of conformal and unconformal surface at the Base of Eocene marks the disappearance of the *Interior Seaway* in the western part of the continent. South America displays a gradual growth with time in the ratio of conformable surface relative to the total area of conformal and unconformal surface. The lack of signal at the Base of Eocene and the Base of Oligocene, which we noted before in the BHS (figure 6d,e), is evinced in figure 8 by the drop in the grey curve reporting the ratio of the total conformal and unconformal surface relative to the total area of South America. Europe's ratio of conformable surface relative to the total area of conformal and unconformal surface sinks dramatically at the Base Eocene, in agreement with the continent-scale growth of unconformable surface and the implied Eocene subsidence that followed the arrival of the Iceland Plume. Africa incurs two increases in the ratio of unconformable surface relative to the total conformal and unconformal surface at the Base of Upper Cretaceous and the Base of Miocene, presumably reflecting Upper Cretaceous and Miocene subsidence as discussed before. Notable for Australia is the increase in the ratio of conformable surface to the total un/conformable surface at the Base of Upper Cretaceous, attributed to Australia's eastward passage over subducted oceanic lithosphere. These results are in broad agreement with the analyses of [75,76] and support the notion that there are no stable continental platforms [101].

In our discussion, we must point to the severe limitations of our method. First: GHMs strongly depend on the spatio-temporal resolution and accuracy of data compiled on geological maps. This means that the duration over which a particular hiatus area is defined depends on the temporal resolution of the input geological map, as noted before (figure 3). Our analysis is limited to the series level. But true hiatus is likely longer than indicated by the missing series, because at any one location sedimentary successions represent only a small portion of a series. This implies large temporal uncertainties in our analysis, even when only one series is absent or when the adjacent series is not fully represented in the field. While our saturation of the time intervals to the series level is dictated by the data (i.e. the geological convention), it inevitably hides shorter duration lacunae and thereby avoids artefacts related to the Sadler effect [102]. This is critical, because if shorter duration lacunae are hidden, shorter duration events from lithospheric processes may be conflated with longer duration mantle-driven signals. Essentially our method favours large time intervals and hides shorter time intervals. Krob *et al.* [103] deduced an uplift duration signal of

50 Myrs for the Parana-Etendeka plume. So even at the temporal resolution of series it may be difficult to detect plume-related uplift events. A similar difficulty arises when continents move laterally over different dynamic topography domains in relatively short geological time frames [104]. Future stratigraphic work should therefore respond to the geodynamic need for more precise dating of hiatus. Interregional geological maps at the resolution of stages (1–2 Myrs) are needed to reduce the uncertainties and to assist in geodynamic interpretations of hiatus.

Second: GHMs on their own do not identify the lithospheric or sublithospheric causes for continental vertical motion. Models predicting continental rise under increased horizontal stress (e.g. [105]), lithospheric folding [106] or delamination (e.g. [107,108]), which act as tectonic mechanisms within the lithosphere, must be distinguished from deeper, mantle-related effects, such as the influence of rising plumes or pressure-driven asthenosphere flow. Detailed biostratigraphy and geomorphological methods of slope investigation or planation surfaces [109] are needed in the identification of broad scale (tectonic) structures in the sense of Şengör [37]. It is clear that viable dynamic models of lithosphere motion must provide for a coupling of tectonic and mantle-related forces (e.g. [110]) to represent the behaviour of the lithosphere as the combination of lithospheric and sublithospheric effects.

Third: GHMs are well constrained in lateral extent but not in amplitude. The latter requires independent calibration, for example, by using thermochronological data [111]. A variety of inferences provide constraints on surface uplift of the lithosphere. They include studies of river profiles (e.g. [112]), sediment compaction [113] and provenance [26,114], landform analysis [109] based on planation surfaces [115], paleoaltimetry [116], or the analysis of sediment budgets at the scale of continental margins [117–119]. Passive margins have been advocated as suitable locations for such studies [18]. MacGregor [120] summarizes episodes of margin uplift for South America and Africa, and similar inferences have been made for the Arctic [121] and the European passive margin of the North Atlantic, summarized in the Stratagem project ([122] and references therein). Inferences for an active post-rift evolution of passive margins have been collected into propositions for geodynamic models [123]. Geological hiatus maps suggest to extend the studies to broader spatial scales beyond passive margins.

(a) Geodynamic implications

Geodynamicists explore mantle convection in terms of the plate and plume modes. Hiatus maps reveal the plate mode as broad conformable surfaces at the Base of Upper Cretaceous in Australia (figure 6g) and the Base of Paleocene in western North America (figure 6f), as noted before. Unconformable surfaces and areas of lack of signal located away from active plate margins are instead expressions of the plume mode. Seismic evidence suggests a strong plume mode [12–14], imaged for the upper [124–126] and the lower mantle as prominent regions of seismically slow velocities (e.g. [127–130]). The geodynamic analysis of these anomalies remains under debate and permits interpretations of the lower mantle anomalies primarily by elevated temperature [129,131,132] or combinations of thermal and compositional effects [133,134]. The repeated appearance of continent-scale hiatus surfaces in our maps provides additional constraints. It implies significant positive mantle buoyancies presumably related to elevated temperature.

The distribution of unconformable surface varies at the timescale of geologic series, (i.e. ten to a few tens of Myrs). This is considerably faster than the mantle transit time which, as the timescale for convection, is about 100–200 Myrs [38,135]. The difference in the convective timescale and the timescale for topography in convective support is illustrated by geodynamic kernels. They reflect the properties of dynamic Earth models and depend strongly upon the assumed rheology (see [136] for a review). For internal loads (e.g. hot rising plumes or cold sinking slabs) passing through a uniform-viscosity mantle, the kernels predict a continuous evolution of the induced surface deflections. In other words, a comparable timescale for convection and convectively maintained topography is implied and borne out in laboratory models of isoviscous mantle flow [137]. The presence of a weaker upper mantle relative to the lower mantle, which is consistent with inferences from geodynamics [62] and mineral physics modelling [138], amplifies surface

deflections for loads passing through the upper mantle. This property of dynamic Earth models makes rapid changes of convectively maintained topography geodynamically plausible.

Geological hiatus maps have implications for time-dependent geodynamic Earth models: progress has been made in understanding how to retrodict past mantle states. Early backward advection schemes (e.g. [139,140]) have given way to a formal inverse problem based on adjoint equations that provide sensitivity information in a geodynamic model relative to earlier system states. Adjoint equations have been derived for incompressible [141–143], compressible [144] and thermo-chemical [145] mantle flow, and the uniqueness property of the inverse problem has been related to the tangential component of the surface velocity field of the convection model [146]. Knowledge of the latter is essential to ensure convergence [147,148]. While plate motions are a primary surface expression of mantle convection (e.g. [3]), one needs to assimilate the tangential component of the surface velocity field (i.e. a past plate motion model) to solve the inverse problem. This makes past plate motions the input of retrodictions rather than their output, and suggests linking viable tests of retrodictions to inferences of past dynamic topography so that uncertain model parameters and state estimates can be assessed [149]. Put differently: the horizontal motion of the lithosphere cannot be predicted from mantle flow restorations, because reconstructions of past plate motion act as an input to the inverse problem, implying that it is not viable to construct self-consistent models of plate tectonics that are testable against the geologic record. However, mantle convection also induces vertical motion in the form of dynamic topography, as noted before. These can be inferred from a mantle flow retrodiction, because they are an output of the inverse problem. Geologic constraints on the history of convectively induced vertical motion of the lithosphere (that is the evolution of past dynamic topography) therefore are crucial observations to test the validity of the geodynamic modelling parameters assumed in mantle flow retrodictions. Our results imply that changes in convectively maintained topography at the timescale of geologic series and over spatial scales of a few thousand kilometres must be an integral component of time-dependent geodynamic Earth models.

5. Conclusion

The analysis of continent-scale geological maps yields powerful information for constraining large-scale geodynamic processes and models. By providing consistent compilations of geologic observations at the scale of thousands of kilometres, continent-scale geologic maps link naturally to large-scale mantle flow-induced elevation changes known as ‘dynamic topography’ [16,17]. While the latter is difficult to separate by geophysical or geodetic means from the current isostatic topography of our planet outside the oceanic realm [63], its transient nature leaves signals in sedimentary archives as conformable and unconformable (hiatus) time boundaries traceable over hundreds to thousands of kilometres. We have applied a hiatus mapping method, introduced by [30,31], as a first-order technique that uses a single manipulation of existing geological maps to construct hiatus surfaces at the temporal resolution of series across North and South America, Europe, Africa and Australia starting from the Upper Jurassic. We find significant differences in the spatial extent of hiatus surface across and between continents at the timescale of geologic series, ten to a few tens of Myrs. This is considerably smaller than the mantle transit time [38] and may reflect the effects of rapid lateral motion of continents over different dynamic topography domains in relatively short geological time-frames [104] as well as vigorous upper mantle flow in the asthenosphere facilitated by a viscosity reduction from the lower to the upper mantle as implied by response functions for dynamic Earth models (e.g. [62]). The recurrent appearance of continent-scale hiatus surfaces is consistent with the existence of significant positive mantle buoyancies, presumably induced by thermal effects and elevated temperature. This supports the notion of a strong plume mode in the mantle convection system. In the future, it is necessary to compile interregional geological maps at the temporal resolution of stages, most of which span 1–2 Myrs in duration, to reduce uncertainty and to assist in improved geodynamic interpretations of hiatus through time-dependent geodynamic Earth models capable of retrodicting past mantle flow states.

Data accessibility. As electronic supplementary material the fully normalized spherical harmonics coefficients [61] are provided for the base of each geological time series for the Cenozoic and Cretaceous.

Competing interests. We declare we have no competing interests.

Funding. This research has been supported by the European Union's Horizon 2020 Research and Innovation Programme under the ERC-2019-STG project TEAR, grant no. 852992.

Acknowledgements. The authors thank the two reviewers, A.M.C. Şengör and S. Zahirovic, the editor J. Braun, as well as G. Meinhold, L. Colli and S. Ghelichkhan for their constructive comments on the manuscript.

References

1. Turcotte DL, Oxburgh ER. 1967 Finite amplitude convective cells and continental drift. *J. Fluid Mech.* **28**, 29–42. (doi:10.1017/S0022112067001880)
2. Davies GF. 1988 Ocean bathymetry and mantle convection: 1. Large-scale flow and hotspots. *J. Geophys. Res.* **93**, 10 467–10 480. (doi:10.1029/JB093iB09p10467)
3. Davies GF, Richards MA. 1992 Mantle convection. *J. Geol.* **100**, 151–206. (doi:10.1086/629582)
4. Davies GF. 1999 *Dynamic Earth: plates, plumes and mantle convection*. Cambridge, UK: Cambridge University Press.
5. Gordon RG, Jurdy DM. 1986 Cenozoic global plate motions. *J. Geophys. Res.: Solid Earth* **91**, 12389–12406. (doi:10.1029/JB091iB12p12389)
6. Müller RD *et al.* 2016 Ocean basin evolution and global-scale plate reorganization events since Pangea breakup. *Annu. Rev. Earth Planet. Sci.* **44**, 107–138. (doi:10.1146/annurev-earth-060115-012211)
7. Richards MA, Engebretson DC. 1992 Large-scale mantle convection and the history of subduction. *Nature* **355**, 437–440. (doi:10.1038/355437a0)
8. Lithgow-Bertelloni C, Richards MA. 1998 The dynamics of Cenozoic and Mesozoic plate motions. *Rev. Geophys.* **36**, 27–78. (doi:10.1029/97RG02282)
9. Bunge HP, Richards MA, Lithgow-Bertelloni C, Baumgardner JR, Grand SP, Romanowicz BA. 1998 Time scales and heterogeneous structure in geodynamic earth models. *Science* **280**, 91–95. (doi:10.1126/science.280.5360.91)
10. McNamara AK, Zhong S. 2005 Degree-one mantle convection: dependence on internal heating and temperature-dependent rheology. *Geophys. Res. Lett.* **32**, L01301. (doi:10.1029/2004GL021082)
11. Bower DJ, Gurnis M, Seton M. 2013 Lower mantle structure from paleogeographically constrained dynamic Earth models. *Geochem. Geophys. Geosyst.* **14**, 44–63. (doi:10.1029/2012GC004267)
12. French SW, Romanowicz BA. 2015 Broad plumes rooted at the base of the Earth's mantle beneath major hotspots. *Nature* **525**, 95–99. (doi:10.1038/nature14876)
13. Nelson PL, Grand SP. 2018 Lower-mantle plume beneath the Yellowstone hotspot revealed by core waves. *Nat. Geosci.* **11**, 280–284. (doi:10.1038/s41561-018-0075-y)
14. Rickers F, Fichtner A, Trampert J. 2013 The Iceland-Jan Mayen plume system and its impact on mantle dynamics in the North Atlantic region: evidence from full-waveform inversion. *Earth Planet. Sci. Lett.* **367**, 39–51. (doi:10.1016/j.epsl.2013.02.022)
15. Pekeris CL. 1935 Thermal convection in the interior of the Earth. *Geophys. J. Int.* **3**, 343–367. (doi:10.1111/j.1365-246X.1935.tb01742.x)
16. Hager BH, Clayton RW, Richards MA, Comer RP, Dziewonski AM. 1985 Lower mantle heterogeneity, dynamic topography and the geoid. *Nature* **313**, 541–545. (doi:10.1038/313541a0)
17. Braun J. 2010 The many surface expressions of mantle dynamics. *Nat. Geosci.* **3**, 825–833. (doi:10.1038/ngeo1020)
18. Bunge HP, Glasmacher UA. 2018 Models and observations of vertical motion (MoveOn) associated with rifting to passive margins: preface. *Gondwana Res.* **53**, 1–8. (doi:10.1016/j.gr.2017.07.005)
19. Mitrovica JX, Beaumont C, Jarvis GT. 1989 Tilting of continental interiors by the dynamical effects of subduction. *Tectonics* **8**, 1079–1094. (doi:10.1029/TC008i005p01079)
20. Burgess PM, Gurnis M, Moresi L. 1997 Formation of sequences in the cratonic interior of North America by interaction between mantle, eustatic, and stratigraphic processes. *Geol. Soc. Am. Bull.* **109**, 1515–1535. (doi:10.1130/0016-7606(1997)109<1515:FOSITC>2.3.CO;2)

21. Gurnis M, Müller RD, Moresi L. 1998 Cretaceous vertical motion of Australia and the Australian-Antarctic discordance. *Science* **279**, 1499–1504. (doi:10.1126/science.279.5356.1499)
22. Harrington L, Zahirovic S, Salles T, Braz C, Müller RD. 2019 Tectonic, geodynamic and surface process driving forces of Australia's paleogeography since the Jurassic. In *The Sedimentary Basins of Western Australia V: Proc. of the Petroleum Exploration Society of Australia Symp., Perth, WA* (eds M Keep, S Moss), p. 29.
23. Clements B, Burgess PM, Hall R, Cottam MA. 2011 Subsidence and uplift by slab-related mantle dynamics: a driving mechanism for the Late Cretaceous and Cenozoic evolution of continental SE Asia? *Geol. Soc. Lond. Special Publ.* **355**, 37–51. (doi:10.1144/SP355.3)
24. Müller RD, Hassan R, Gurnis M, Flament N, Williams SE. 2018 Dynamic topography of passive continental margins and their hinterlands since the Cretaceous. *Gondwana Res.* **53**, 225–251. (doi:10.1016/j.gr.2017.04.028)
25. Cox KG. 1989 The role of mantle plumes in the development of continental drainage patterns. *Nature* **342**, 873–877. (doi:10.1038/342873a0)
26. Şengör AMC. 2001 Elevation as indicator of mantle-plume activity In *Mantle plumes: Their identification through time*, vol. 352, pp. 183–245
27. Rainbird RH, Ernst RE. 2001 The sedimentary record of mantle-plume uplift. *Special Papers-Geol. Soc. Am.* **352**, 227–246. (doi:10.1130/0-8137-2352-3.227)
28. Saunders AD, Jones SM, Morgan LA, Pierce KL, Widdowson M, Xu YG. 2007 Regional uplift associated with continental large igneous provinces: the roles of mantle plumes and the lithosphere. *Chem. Geol.* **241**, 282–318. (doi:10.1016/j.chemgeo.2007.01.017)
29. Miall AD. 2016 The valuation of unconformities. *Earth Sci. Rev.* **163**, 22–71. (doi:10.1016/j.earscirev.2016.09.011)
30. Friedrich AM, Bunge HP, Rieger SM, Colli L, Ghelichkhan S, Nerlich R. 2018 Stratigraphic framework for the plume mode of mantle convection and the analysis of interregional unconformities on geological maps. *Gondwana Res.* **53**, 159–188. (doi:10.1016/j.gr.2017.06.003)
31. Friedrich AM. 2019 Palaeogeological hiatus surface mapping: a tool to visualize vertical motion of the continents. *Geol. Mag.* **156**, 308–319. (doi:10.1017/S0016756818000560)
32. Sloss LL. 1963 Sequences in the cratonic interior of North America. *Geol. Soc. Am. Bull.* **74**, 93–114. (doi:10.1130/0016-7606(1963)74[93:SITCIO]2.0.CO;2)
33. Sloss L. 1972 Synchrony of Phanerozoic sedimentary-tectonic events of the North American Craton and the Russian platform. In *24th Int. Geological Congress, Montreal*, vol. 6, pp. 24–32.
34. Vibe Y, Friedrich AM, Bunge HP, Clark SR. 2018 Correlations of oceanic spreading rates and hiatus surface area in the North Atlantic realm. *Lithosphere* **10**, 677–684. (doi:10.1130/L736.1)
35. Carena S, Bunge HP, Friedrich AM. 2019 Analysis of geological hiatus surfaces across Africa in the Cenozoic and implications for the timescales of convectively-maintained topography. *Can. J. Earth Sci.* **56**, 1333–1346. (doi:10.1139/cjes-2018-0329)
36. Asch K. 2004 IGME 5000. 1:5 million international geological map of Europe and adjacent areas. BGR (Hannover).
37. Şengör AMC. 2003 *The large wavelength deformations of the Lithosphere: Materials for a history of the evolution of thought from the earliest times to plate tectonics*. Geological Society of America, Memoir no. 196.
38. Iaffaldano G, Bunge HP. 2015 Rapid plate motion variations through geological time: observations serving geodynamic interpretation. *Annu. Rev. Earth Planet. Sci.* **43**, 571–592. (doi:10.1146/annurev-earth-060614-105117)
39. Stille H. 1919 Die Begriffe Orogenese und Epirogenese. *Zeitschrift der Deutschen Geologischen Gesellschaft* **71**, 164–208.
40. Stille H. 1924 Grundfragen der Vergleichenden Tektonik. *Gebäude Borntraeger* **71**, 1–443.
41. Raymond OL, Gallagher R, Shaw R, Yeates AN, Douth HF, Palfreyman WD, Blake DH, Highet L. 2012 Surface geology of Australia 1:2.5 million scale dataset 2012 edition. Commonwealth of Australia (Geoscience Australia).
42. Garrity CP, Soller DR. 2009 Database of the geologic map of North America, adapted from the map by JC Reed Jr and others (2005). Reston, VA: U.S. Geological Survey.
43. SEGEMAR, Servicio Geológico Minero Argentino. 2017 Mapa geológico de Argentina. San Martín, Argentina.
44. Claire Zapata M, Lema Patiño R, Riera Kilibarda C, Suarez Soruco R. 2012 Mapa geológico de Bolivia, 2000. SERGEOMIN, Servicio Geológico Minero. La Paz, Bolivia.

45. CPRM, Serviço Geológico do Brasil. 2010 Carta geológica do Brasil ao milionésimo. Brasília, Brazil.
46. SERNAGEOMIN, Servicio Nacional de Geología y Minería. 2003 Mapa geológico de Chile: Versión digital. Santiago, Chile.
47. Jorge G, Montes Ramírez N, Almanza Meléndez M, Alcárcel Gutiérrez F, Madrid Montoya C, Diederix H. 2015 Geological map of Colombia 2015. *J. Int. Geosci.* **40**, 201–212. (doi:10.18814/epiugs/2017/v40i3/017023)
48. MAGAP, Ministerio de Agricultura y Ganadería. 2005 Mapa hidrogeológico de Ecuador. Quito, Ecuador.
49. INGEMMET, Instituto Geológico, Minero y Metalúrgico. 2016 GEOCATMIN: Geología nacional millón 1:1.000.000, Perú, 2016. Lima, Peru.
50. Loureiro J, Pérez Cerdán F, Spoturno J, Faraone M, Guerrero S, Sánchez Bettucci L. 2016 Versión digital y actualización del mapa geológico del Uruguay de DINAMIGE a escala 1:500.000. In *VIII Congreso Uruguayo de Geología 2016*. MIEM, Ministerio de Industria, Energía y Minería. Montevideo, Uruguay.
51. Hackley P, Urbani F, Karlsen AW, Garrity CP. 2004 Geological shaded relief map of Venezuela. *USGS Open File Report* **2005**, 1–2.
52. Ocean Drilling Program. 1985–2004 Ocean Drilling Program (ODP). Legs 100–210, Sites 625–1277.
53. Deep Sea Drilling Project. 1968–1983 Deep Sea Drilling Project (DSDP). Legs 1–96, Sites 1–624.
54. Cohen KM, Harper D, Gibbard PL. 2018/08 ICS international chronostratigraphic chart. See <http://www.stratigraphy.org>.
55. Ogg JG, Ogg GM, Gradstein FM. 2016 1 - Introduction. In *A Concise Geologic Time Scale* (eds JG Ogg, GM Ogg, FM Gradstein), pp. 1–8. Elsevier.
56. DeMets C, Gordon RG, Argus DF. 2010 Geologically current plate motions. *Geophys. J. Int.* **181**, 1–80. (doi:10.1111/j.1365-246X.2009.04491.x)
57. O'Neill C, Müller RD, Steinberger B. 2005 On the uncertainties in hot spot reconstructions and the significance of moving hot spot reference frames. *Geochem. Geophys. Geosyst.* **6**, Q04003. (doi:10.1029/2004GC000784)
58. Müller RD *et al.* 2018 GPlates: building a virtual Earth through deep time. *Geochem. Geophys. Geosyst.* **19**, 2243–2261. (doi:10.1029/2018GC007584)
59. Burke K, Torsvik TH. 2004 Derivation of Large Igneous Provinces of the past 200 million years from long-term heterogeneities in the deep mantle. *Earth Planet. Sci. Lett.* **227**, 531–538. (doi:10.1016/j.epsl.2004.09.015)
60. Wiczeorek MA, Meschede M. 2018 Shtools: tools for working with spherical harmonics. *Geochem. Geophys. Geosyst.* **19**, 2574–2592. (doi:10.1029/2018GC007529)
61. Stacey FD, Davis PM. 2008 *Physics of the Earth*. New York, NY: Cambridge University Press.
62. Richards MA, Hager BH. 1984 Geoid anomalies in a dynamic Earth. *J. Geophys. Res.: Solid Earth* **89**, 5987–6002. (doi:10.1029/JB089iB07p05987)
63. Hoggard MJ, Winterbourne J, Czarnota K, White N. 2017 Oceanic residual depth measurements, the plate cooling model, and global dynamic topography. *J. Geophys. Res.: Solid Earth* **122**, 2328–2372. (doi:10.1002/2016JB013457)
64. Courtillot V, Davaille A, Besse J, Stock J. 2003 Three distinct types of hotspots in the Earth's mantle. *Earth Planet. Sci. Lett.* **205**, 295–308. (doi:10.1016/S0012-821X(02)01048-8)
65. Müller RD, Sdrolias M, Gaina C, Steinberger B, Heine C. 2008 Long-term sea-level fluctuations driven by ocean basin dynamics. *Science* **319**, 1357–1362. (doi:10.1126/science.1151540)
66. Rowley DB. 2017 Earth's constant mean elevation: implication for long-term sea level controlled by oceanic lithosphere dynamics in a Pitman world. *J. Geol.* **125**, 141–153. (doi:10.1086/690197)
67. Petersen SV, Schrag DP. 2015 Antarctic ice growth before and after the Eocene-Oligocene transition: new estimates from clumped isotope paleothermometry. *Paleoceanography* **30**, 1305–1317. (doi:10.1002/2014PA002769)
68. Maslin MA, Haug GH, Sarnthein M, Tiedemann R. 1996 The progressive intensification of northern hemisphere glaciation as seen from the North Pacific. *Geol. Rundsch.* **85**, 452–465. (doi:10.1007/BF02369002)
69. Ricard Y, Fleitout L, Froidevaux C. 1984 Geoid heights and lithospheric stresses for a dynamic Earth. *Ann. Geophys.* **2**, 267–286.

70. Forte AM, Peltier R. 1991 Viscous flow models of global geophysical observables: 1. Forward problems. *J. Geophys. Res.: Solid Earth* **96**, 20131–20159. (doi:10.1029/91JB01709)
71. Fishwick S, Bastow ID. 2011 Towards a better understanding of African topography: a review of passive-source seismic studies of the African crust and upper mantle. *Geol. Soc. Lond. Special Publ.* **357**, 343–371. (doi:10.1144/SP357.19)
72. Ravenna M, Lebedev S, Fulla J, Adam JMC. 2018 Shear-wave velocity structure of southern Africa's lithosphere: variations in the thickness and composition of cratons and their effect on topography. *Geochem. Geophys. Geosyst.* **19**, 1499–1518. (doi:10.1029/2017GC007399)
73. Jones AG, Afonso JC, Fulla J. 2017 Geochemical and geophysical constraints on the dynamic topography of the Southern African Plateau. *Geochem. Geophys. Geosyst.* **18**, 3556–3575. (doi:10.1002/2017GC006908)
74. Molnar P, England PC, Jones CH. 2015 Mantle dynamics, isostasy, and the support of high terrain. *J. Geophys. Res.: Solid Earth* **120**, 1932–1957. (doi:10.1002/2014JB011724)
75. Bond GC. 1978 Speculations on real sea-level changes and vertical motions of continents at selected times in the Cretaceous and Tertiary Periods. *Geology* **6**, 247–250. (doi:10.1130/0091-7613(1978)6<247:SORSCA>2.0.CO;2)
76. Bond GC. 1979 Evidence for some uplifts of large magnitude in continental platforms. *Tectonophysics* **61**, 285–305. (doi:10.1016/0040-1951(79)90302-0)
77. Bond GC. 1978 Evidence for late Tertiary uplift of Africa relative to North America, South America, Australia and Europe. *J. Geol.* **86**, 47–65. (doi:10.1086/649655)
78. Burke K, Whiteman AJ. 1973 Uplift, rifting and break-up of Africa. In *Implications of Continental Drift to the Earth Sciences* (eds DH Tarling, SK Runcorn). London & New York: Academic Press.
79. Suess E. 1883 *Das Antlitz der Erde: Erster Band*. F. Tempsky, Prag und Wien, and G. Freytag, Leipzig.
80. Blackwelder E. 1909 The valuation of unconformities. *J. Geol.* **17**, 289–299. (doi:10.1086/621610)
81. Levorsen AI. 1933 Studies in paleogeology. *AAPG Bull.* **17**, 1107–1132. (doi:10.1306/3D932BA2-16B1-11D7-8645000102C1865D)
82. Wheeler HE. 1958 Time-stratigraphy. *AAPG Bull.* **42**, 1047–1063. (doi:10.1306/0BDA5AF2-16BD-11D7-8645000102C1865D)
83. Belousov VV, Maxwell JC. 1962 *Basic problems in geotectonics*. New York, NY: McGraw-Hill.
84. Sloss LL. 1992 Tectonic episodes of cratons: conflicting North American concepts. *Terra Nova* **4**, 320–328. (doi:10.1111/j.1365-3121.1992.tb00821.x)
85. Vail PR, Mitchum Jr RM, Thompson III S. 1977 Seismic stratigraphy and global changes of sea level: Part 4. Global cycles of relative changes of sea level: §2. Application of seismic reflection configuration to stratigraphic interpretation. In *Seismic Stratigraphy: Applications to Hydrocarbon Exploration*, pp. 83–97. American Association of Petroleum Geologists, Memoir no. 26.
86. Şengör AMC. 2016 What is the use of the history of geology to a practicing geologist? The propaedeutical case of stratigraphy. *J. Geol.* **124**, 643–698. (doi:10.1086/688609)
87. Colli L, Stotz I, Bunge HP, Smethurst M, Clark SR, Iaffaldano G, Tassara A, Guillocheau F, Bianchi MC. 2014 Rapid South Atlantic spreading changes and coeval vertical motion in surrounding continents: evidence for temporal changes of pressure-driven upper mantle flow. *Tectonics* **33**, 1304–1321. (doi:10.1002/2014TC003612)
88. Barker PF. 1983 Tectonic evolution and subsidence history of the Rio-Grande Rise. Initial Reports of the Deep Sea Drilling Project 72, 953–976. (doi:10.2973/dsdp.proc.72.151.1983)
89. Cogné N, Gallagher K, Cobbold PR, Riccomini C, Gautheron C. 2012 Post-breakup tectonics in southeast Brazil from thermochronological data and combined inverse-forward thermal history modeling. *J. Geophys. Res.: Solid Earth* **117**, B11413. (doi:10.1029/2012JB009340)
90. Japsen P, Bonow JM, Green PF, Cobbold PR, Chiossi D, Lilletveit R, Magnavita LP, Pedreira A. 2012 Episodic burial and exhumation in NE Brazil after opening of the South Atlantic. *Bulletin* **124**, 800–816. (doi:10.1130/B30515.1)
91. Krob FC, Glasmacher UA, Karl M, Perner M, Hackspacher PC, Stockli DF. 2019 Multi-chronometer thermochronological modelling of the Late Neoproterozoic to recent t-T evolution of the SE coastal region of Brazil. *J. South Am. Earth Sci.* **92**, 77–94. (doi:10.1016/j.jsames.2019.02.012)
92. Kollenz S, Glasmacher UA, Rossello EA, Stockli DF, Schad S, Pereyra RE. 2017 Thermochronological constraints on the Cambrian to recent geological evolution of the

- Argentina passive continental margin. *Tectonophysics* **716**, 182–203. (doi:10.1016/j.tecto.2016.11.019)
93. Horton BK. 2018 Sedimentary record of Andean mountain building. *Earth Sci. Rev.* **178**, 279–309. (doi:10.1016/j.earscirev.2017.11.025)
 94. Baby G, Guillocheau F, Boulogne C, Robin C, Dall'Asta M. 2018 Uplift history of a transform continental margin revealed by the stratigraphic record: the case of the Agulhas transform margin along the Southern African Plateau. *Tectonophysics* **731**, 104–130. (doi:10.1016/j.tecto.2018.03.014)
 95. Gallagher K, Brown R. 1999 Denudation and uplift at passive margins: the record on the Atlantic Margin of Southern Africa. *Phil. Trans. R. Soc. Lond. A* **357**, 835–859. (doi:10.1098/rsta.1999.0354)
 96. Tinker J, de Wit M, Brown R. 2008 Mesozoic exhumation of the southern Cape, South Africa, quantified using apatite fission track thermochronology. *Tectonophysics* **455**, 77–93. (doi:10.1016/j.tecto.2007.10.009)
 97. Burke K, Gunnell Y. 2008 *The African erosion surface: a continental-scale synthesis of geomorphology, tectonics, and environmental change over the past 180 million years*, vol. 201. Boulder, CO: Geological Society of America.
 98. Matthews KJ, Hale AJ, Gurnis M, Müller RD, DiCaprio L. 2011 Dynamic subsidence of Eastern Australia during the Cretaceous. *Gondwana Res.* **19**, 372–383. (doi:10.1016/j.gr.2010.06.006)
 99. Heine C, Müller RD, Steinberger B, DiCaprio L. 2010 Integrating deep Earth dynamics in paleogeographic reconstructions of Australia. *Tectonophysics* **483**, 135–150. (doi:10.1016/j.tecto.2009.08.028)
 100. Spasojevic S, Liu L, Gurnis M. 2009 Adjoint models of mantle convection with seismic, plate motion, and stratigraphic constraints: North America since the Late Cretaceous. *Geochim. Geophys. Geosyst.* **10**, Q05W02. (doi:10.1029/2008GC002345)
 101. Moucha R, Forte AM, Mitrovica JX, Rowley DB, Quéré S, Simmons NA, Grand SP. 2008 Dynamic topography and long-term sea-level variations: there is no such thing as a stable continental platform. *Earth Planet. Sci. Lett.* **271**, 101–108. (doi:10.1016/j.epsl.2008.03.056)
 102. Sadler PM. 1981 Sediment accumulation rates and the completeness of stratigraphic sections. *J. Geol.* **89**, 569–584. (doi:10.1086/628623)
 103. Krob FC, Glasmacher UA, Bunge HP, Friedrich AM, Hackspacher PC. 2020 Application of stratigraphic frameworks and thermochronological data on the Mesozoic SW Gondwana intraplate environment to retrieve the Paraná-Etendeka plume movement. *Gondwana Res.* **84**, 81–110. (doi:10.1016/j.gr.2020.02.010)
 104. Braun J, Guillocheau F, Robin C, Baby G, Jelsma H. 2014 Rapid erosion of the Southern African Plateau as it climbs over a mantle superswell. *J. Geophys. Res.: Solid Earth* **119**, 6093–6112. (doi:10.1002/2014JB010998)
 105. Ziegler PA, Cloetingh S, van Wees JD. 1995 Dynamics of intra-plate compressional deformation: the Alpine foreland and other examples. *Tectonophysics* **252**, 7–59. (doi:10.1016/0040-1951(95)00102-6)
 106. Cloetingh S, Burov E, Beekman F, Andeweg B, Andriessen P, Garcia-Castellanos D, de Vicente G, Vegas R. 2002 Lithospheric folding in Iberia. *Tectonics* **21**, 5-1–5-26. (doi:10.1029/2001TC901031)
 107. Levander A, Schmandt B, Miller MS, Liu K, Karlstrom KE, Crow RS, Lee CTA, Humphreys ED. 2011 Continuing Colorado plateau uplift by delamination-style convective lithospheric downwelling. *Nature* **472**, U461–U540. (doi:10.1038/nature10001)
 108. Schott B, Schmeling H. 1998 Delamination and detachment of a lithospheric root. *Tectonophysics* **296**, 225–247. (doi:10.1016/S0040-1951(98)00154-1)
 109. Guillocheau F, Simon B, Baby G, Bessin P, Robin C, Dauteuil O. 2018 Planation surfaces as a record of mantle dynamics: the case example of Africa. *Gondwana Res.* **53**, 82–98. (doi:10.1016/j.gr.2017.05.015)
 110. Stotz IL, Iaffaldano G, Davies DR. 2017 Late Miocene Pacific plate kinematic change explained with coupled global models of mantle and lithosphere dynamics. *Geophys. Res. Lett.* **44**, 7177–7186. (doi:10.1002/2017GL073920)
 111. Ehlers TA, Farley KA. 2003 Apatite (U–Th)/He thermochronometry: methods and applications to problems in tectonic and surface processes. *Earth Planet. Sci. Lett.* **206**, 1–14. (doi:10.1016/S0012-821X(02)01069-5)

112. Roberts GG, White N. 2010 Estimating uplift rate histories from river profiles using African examples. *J. Geophys. Res.: Solid Earth* **115**, B02406. (doi:10.1029/2009JB006692)
113. Japsen P. 2018 Sonic velocity of chalk, sandstone and marine shale controlled by effective stress: velocity-depth anomalies as a proxy for vertical movements. *Gondwana Res.* **53**, 145–158. (doi:10.1016/j.gr.2017.04.013)
114. Meinhold G. 2010 Rutile and its applications in Earth sciences. *Earth–Sci. Rev.* **102**, 1–28. (doi:10.1016/j.earscirev.2010.06.001)
115. King LC. 1955 Pediplanation and isostasy: an example from South Africa. *Q. J. Geol. Soc.* **111**, 353–359. (doi:10.1144/GSL.JGS.1955.111.01-04.18)
116. Kohn MJ ed. 2018 *Paleoaltimetry: geochemical and thermodynamic approaches*, vol. 66. Reviews in Mineralogy and Geochemistry. De Gruyter.
117. Guillocheau F, Rouby D, Robin C, Helm C, Rolland N, Le Carlier de Veslud C, Braun J. 2012 Quantification and causes of the terrigenous sediment budget at the scale of a continental margin: a new method applied to the Namibia–South Africa margin. *Basin Res.* **24**, 3–30. (doi:10.1111/j.1365-2117.2011.00511.x)
118. Said A, Moder C, Clark S, Abdelmalak MM. 2015a Sedimentary budgets of the Tanzania coastal basin and implications for uplift history of the East African rift system. *J. Afr. Earth. Sci.* **111**, 288–295. (doi:10.1016/j.jafrearsci.2015.08.012)
119. Said A, Moder C, Clark S, Ghorbal B. 2015b Cretaceous–Cenozoic sedimentary budgets of the Southern Mozambique Basin: implications for uplift history of the South African Plateau. *J. Afr. Earth. Sci.* **109**, 1–10. (doi:10.1016/j.jafrearsci.2015.05.007)
120. MacGregor DS. 2013 Late Cretaceous–Cenozoic sediment and turbidite reservoir supply to South Atlantic margins. *Geol. Soc. Lond. Special Publ.* **369**, 109–128. (doi:10.1144/SP369.7)
121. Dörr N, Lisker F, Clift PD, Carter A, Gee DG, Tebenkov AM, Spiegel C. 2012 Late Mesozoic–Cenozoic exhumation history of northern Svalbard and its regional significance: constraints from apatite fission track analysis. *Tectonophysics* **514**, 81–92. (doi:10.1016/j.tecto.2011.10.007)
122. Stoker MS, Shannon PM. 2005 Neogene evolution of the NW European Atlantic margin: results from the STRATAGEM project. *Mar. Pet. Geol.* **22**, 965–968. (doi:10.1016/j.marpetgeo.2005.04.006)
123. Green PF, Japsen P, Chalmers JA, Bonow JM, Duddy IR. 2018 Post-breakup burial and exhumation of passive continental margins: seven propositions to inform geodynamic models. *Gondwana Res.* **53**, 58–81. (doi:10.1016/j.gr.2017.03.007)
124. Schaeffer AJ, Lebedev S. 2013 Global shear speed structure of the upper mantle and transition zone. *Geophys. J. Int.* **194**, 417–449. (doi:10.1093/gji/ggt095)
125. van Herwaarden DP, Boehm C, Afanasiev M, Thrastarson S, Krischer L, Trampert J, Fichtner A. 2020 Accelerated full-waveform inversion using dynamic mini-batches. *Geophys. J. Int.* **221**, 1427–1438. (doi:10.1093/gji/ggaa079)
126. Colli L, Fichtner A, Bunge HP. 2013 Full waveform tomography of the upper mantle in the South Atlantic region: imaging a westward fluxing shallow asthenosphere? *Tectonophysics* **604**, 26–40. (doi:10.1016/j.tecto.2013.06.015)
127. Kennett BLN, Widiyantoro S, van der Hilst RD. 1998 Joint seismic tomography for bulk sound and shear wave speed in the Earth's mantle. *J. Geophys. Res.: Solid Earth* **103**, 12469–12493. (doi:10.1029/98JB00150)
128. Ritsema J, Deuss A, van Heijst HJ, Woodhouse JH. 2011 S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime and normal-mode splitting function measurements. *Geophys. J. Int.* **184**, 1223–1236. (doi:10.1111/j.1365-246X.2010.04884.x)
129. Simmons NA, Forte AM, Grand SP. 2009 Joint seismic, geodynamic and mineral physical constraints on three-dimensional mantle heterogeneity: implications for the relative importance of thermal versus compositional heterogeneity. *Geophys. J. Int.* **177**, 1284–1304. (doi:10.1111/j.1365-246X.2009.04133.x)
130. Hosseini K, Sigloch K, Tsekhmistrenko M, Zaheri A, Nissen-Meyer T, Igel H. 2020 Global mantle structure from multifrequency tomography using P, PP and P-diffracted waves. *Geophys. J. Int.* **220**, 96–141. (doi:10.1093/gji/ggz394)
131. Davies DR, Goes S, Davies JH, Schuberth BSA, Bunge HP, Ritsema J. 2012 Reconciling dynamic and seismic models of Earth's lower mantle: the dominant role of thermal heterogeneity. *Earth Planet. Sci. Lett.* **353**, 253–269. (doi:10.1016/j.epsl.2012.08.016)

132. Schuberth BSA, Bunge HP, Ritsema J. 2009 Tomographic filtering of high-resolution mantle circulation models: can seismic heterogeneity be explained by temperature alone? *Geochem. Geophys. Geosyst.* **10**, Q05W03. (doi:10.1029/2009GC002401)
133. Lu C, Forte AM, Simmons NA, Grand SP, Kajan M, Lai H, Garnero E. 2020 The sensitivity of joint inversions of seismic and geodynamic data to mantle viscosity. *Geochem. Geophys. Geosyst.* **21**, e2019GC008648. (doi:10.1029/2019GC008648)
134. McNamara AK. 2019 A review of large low shear velocity provinces and ultra low velocity zones. *Tectonophysics* **760**, 199–220. (doi:10.1016/j.tecto.2018.04.015)
135. Butterworth NP, Talsma AS, Müller RD, Seton M, Bunge HP, Schuberth BSA, Shephard GE, Heine C. 2014 Geological, tomographic, kinematic and geodynamic constraints on the dynamics of sinking slabs. *J. Geodyn.* **73**, 1–13. (doi:10.1016/j.jog.2013.10.006)
136. Colli L, Ghelichkhan S, Bunge HP. 2016 On the ratio of dynamic topography and gravity anomalies in a dynamic Earth. *Geophys. Res. Lett.* **43**, 2510–2516. (doi:10.1002/2016GL067929)
137. Griffiths RW, Gurnis M, Eitelberg G. 1989 Holographic measurements of surface topography in laboratory models of mantle hotspots. *Geophys. J. Int.* **96**, 477–495. (doi:10.1111/j.1365-246X.1989.tb06009.x)
138. Reali R, Van Orman JA, Pigott JS, Jackson JM, Boioli F, Carrez P, Cordier P. 2019 The role of diffusion-driven pure climb creep on the rheology of bridgmanite under lower mantle conditions. *Sci. Rep.* **9**, 2053. (doi:10.1038/s41598-018-38449-8)
139. Bunge HP, Richards MA. 1992 The backward-problem of plate tectonics and mantle convection, (abstract). *Eos Trans. AGU* **73**, 281. Spring Meeting suppl.
140. Steinberger B, O'Connell RJ. 1997 Changes of the Earth's rotation axis owing to advection of mantle density heterogeneities. *Nature* **387**, 169–173. (doi:10.1038/387169a0)
141. Bunge HP, Hagelberg CR, Travis BJ. 2003 Mantle circulation models with variational data assimilation: inferring past mantle flow and structure from plate motion histories and seismic tomography. *Geophys. J. Int.* **152**, 280–301. (doi:10.1046/j.1365-246X.2003.01823.x)
142. Ismail-Zadeh A, Schubert G, Tsepelev I, Korotkii A. 2004 Inverse problem of thermal convection: numerical approach and application to mantle plume restoration. *Phys. Earth Planet. Inter.* **145**, 99–114. (doi:10.1016/j.pepi.2004.03.006)
143. Horbach A, Bunge HP, Oeser J. 2014 The adjoint method in geodynamics: derivation from a general operator formulation and application to the initial condition problem in a high resolution mantle circulation model. *GEM-Int. J. Geomath.* **5**, 163–194. (doi:10.1007/s13137-014-0061-5)
144. Ghelichkhan S, Bunge HP. 2016 The compressible adjoint equations in geodynamics: derivation and numerical assessment. *GEM-Int. J. Geomath.* **7**, 1–30. (doi:10.1007/s13137-016-0080-5)
145. Ghelichkhan S, Bunge HP. 2018 The adjoint equations for thermochemical compressible mantle convection: derivation and verification by twin experiments. *Proc. R. Soc. A* **474**, 20180329. (doi:10.1098/rspa.2018.0329)
146. Colli L, Bunge HP, Schuberth BSA. 2015 On retrodictions of global mantle flow with assimilated surface velocities. *Geophys. Res. Lett.* **42**, 8341–8348. (doi:10.1002/2015GL066001)
147. Vynnytska L, Bunge HP. 2015 Restoring past mantle convection structure through fluid dynamic inverse theory: regularisation through surface velocity boundary conditions. *GEM-Int. J. Geomath.* **6**, 83–100. (doi:10.1007/s13137-014-0060-6)
148. Colli L, Bunge HP, Oeser J. 2020 Impact of model inconsistencies on reconstructions of past mantle flow obtained using the adjoint method. *Geophys. J. Int.* **221**, 617–639. (doi:10.1093/gji/ggaa023)
149. Colli L, Ghelichkhan S, Bunge HP, Oeser J. 2018 Retrodictions of Mid Paleogene mantle flow and dynamic topography in the Atlantic region from compressible high resolution adjoint mantle convection models: sensitivity to deep mantle viscosity and tomographic input model. *Gondwana Res.* **53**, 252–272. (doi:10.1016/j.gr.2017.04.027)